

A Rectifier Circuit Insensitive to the Angle of Incidence of Incoming Waves Based on a Wilkinson Power Combiner

Spyridon Nektarios Daskalakis, *Student Member, IEEE*, Apostolos Georgiadis, *Senior Member, IEEE* George Goussetis, *Senior Member, IEEE*, and Manos M. Tentzeris, *Fellow, IEEE*

Abstract—In this work a novel high efficiency, low-cost and low-complexity RF-to-dc converter was designed for RF energy harvesting in the 2.4 GHz band. The proposed design has two RF inputs and maintains a high efficiency over a wide range of incoming incident wave angles. The circuit is based on a Wilkinson power combiner and has two single-diode rectifiers. One rectifier is connected at the combiner’s output and collects the energy coming from the two inputs. The second rectifier replaces the isolation resistor of the combiner in order to collect the power that would otherwise be dissipated in it. The second rectifier is used for recycling the wasted power when the input signals do not have the same phase. The novel RF-to-dc converter was fabricated using commercially available components and low-cost FR-4 substrate. A prototype was designed and its efficiency was optimized for low power input levels. The measured system efficiency was 16.2% for in-phase input signals with available input power -17 dBm. When the relative phase of input signals varied from 0 to 360 degrees, a variation in efficiency between 15.3% and 22% was observed. For input power 3 dBm, the efficiency varies from 26% to 39% between 0 to 360 degrees phase difference.

Index Terms—Internet-of-Things (IoT), radio frequency (RF) energy harvesting, radio frequency identification (RFID), rectifier, Wilkinson divider, wireless power transfer.

I. INTRODUCTION

IN our days radio frequency (RF) energy harvesting is an attractive way to capture power in conditions where light or wind sources are not available [1]–[4]. Broadcasting RF transmitters like FM/TV, cellular networks base stations, WiFi routers, and frequency identification (RFID) readers, have been increasing rapidly around us, due to the huge development of wireless technologies. In 1964 William C. Brown proposed a system for transformation of RF power to dc power [5]. In this RF-to-dc converter, an antenna is combined with a rectifier, which consists of one or more diodes in specific

configuration, forming a rectenna. One significant limitation in rectenna design is the relatively low available ambient power density level as well as the RF-to-dc power efficiency of the circuit [4], [6]. It remains an engineering challenge how to capture unused ambient RF energy and use it to supply small sensor nodes, such as radio frequency identification (RFID) tags [4], [7], [8]. Interest in Internet of Things (IoT) low-power sensors powered by RF ambient power or wireless power transmission has increased due to the vision of ubiquitous sensing as part of 5G mobile networks. Wireless powering in the 2.4 GHz industrial, scientific and medical (ISM) band can enable applications where a large number of mobile devices with WiFi/Bluetooth transceivers can act as RF sources to power the sensors.

In most 5G industrial visions, the high energy efficient “Green” performance for 5G systems is pointed out as a necessity both for devices and networks. Consequently RF energy harvesting seems to be a very promising technique for future 5G “Green” systems. In this case, nearby relays are considered which include wireless power transfer capabilities together with the RF communication signals. Millimeter-wave (mmWave) signals could deliver both information and energy to the end small devices, like next generation RFIDs [9], [10]. Such, an RFID device, capable of operating autonomously and with a reading range of tens of meters, would provide a very effective interface point between the IoT and 5G networks [11].

This paper addresses the problem of RF versus dc power combining in rectenna array systems. Increasing the number of antennas and therefore the effective area available for collection of RF energy is a straightforward approach in order to increase the total RF energy that is being harvested. Due to the nonlinear nature of the rectifier circuit however, when the RF energy which is being available to the individual rectenna element is very small, the RF-to-dc conversion efficiency of the rectifier is also very small leading to a non-optimal performance. Therefore, not only the overall number of rectenna elements but the RF power available to each element is important in order to maximize the system efficiency and ultimately the dc output power. As a result, one might first consider rectenna elements where one rectifier is connected to an antenna array thereby achieving superposition of RF energy before the RF-to-dc conversion. For example in [12], the concept of an $N \times N$ staggered pattern charge collector (SPCC) is described in order to achieve maximum energy harvesting

Manuscript received Month DD, YYYY; revised Month DD, YYYY; accepted Month DD, YYYY. This work was supported by Lloyd’s Register Foundation (LRF) and the International Consortium in Nanotechnology (ICON). The work of M. M. Tentzeris was supported by the National Science Foundation (NSF) and the Defense Threat Reduction Agency (DTRA).

This paper is an expanded version from the 2nd URSI Atlantic Radio Science Conference (URSI AT-RASC), Gran Canaria, 28 May - 1 June 2018.

S. N. Daskalakis, G. Goussetis and A. Georgiadis are with School of Engineering & Physical Sciences; Institute of Sensors, Signals and Systems, Heriot-Watt University, Edinburgh, EH14 4AS, Scotland, UK (e-mail: sd70@hw.ac.uk, g.goussetis@hw.ac.uk, apostolos.georgiadis@ieee.org).

M. M. Tentzeris is with School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332-250, USA (e-mail: tentze@ece.gatech.edu).

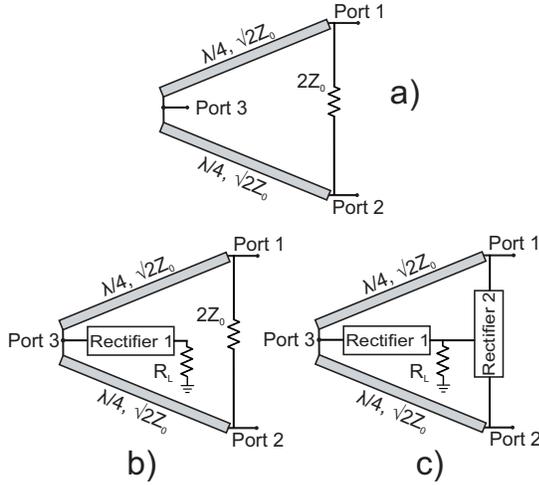


Fig. 1. Power combiner circuits with rectification capabilities. a) Typical Wilkinson combiner circuit. b) Wilkinson combiner circuit with single rectifier c) Wilkinson combiner with two rectifier circuits. One rectifier has been installed at the port 3 and the isolation resistor has been replaced with a second rectifier.

efficiency. Using the above consent, more energy harvesters and thus more diode elements are used in order to cover a wideband area. Another disadvantage of this topology is that superposition of RF energy corresponds to directive antenna elements and one is not able to harvest RF energy coming from different angular directions but only from selected angular directions where the antenna array gain is maximized.

One way around this problem is to employ beam-steering architectures but such systems consume energy in steering the antenna beam and therefore one needs to take into account the amount of energy spent in the beam steering process in order to compute the overall RF-to-dc conversion efficiency of the system. A different approach is to design a sub-array topology where each sub-array is pointed to a fixed but different angular direction. This way one achieves a high efficiency at a fixed predetermined number of angular directions and a good overall efficiency for a range of angular directions at the expense of an increased complexity in the antenna [13].

In this work we demonstrate a scalable, two branch rectifier which is capable of maintaining a constant RF-to-dc conversion efficiency over any phase shift between the RF signals present at its input terminals, and therefore over any angular direction. This topology is able to combine RF energy from any angular direction and convert it efficiently to dc output power. It is based on a Wilkinson power combiner and it is scalable, employing combiner modules connected to a large number of antenna elements or sub-arrays and subsequently combining the output in series or parallel configuration.

In addition to RF power combining our rectifier employs dc power combining at 2.4 GHz by optimally combining the output of two rectifiers in parallel. Our rectifier design could be easily scaled up to mmWave frequencies (i.e. 60 GHz) and miniaturized for a future 5G application. Therefore we propose a rectifier module which provides RF and dc power combining to achieve a high conversion efficiency with minimum variation from RF signals with arbitrary phase, thereby

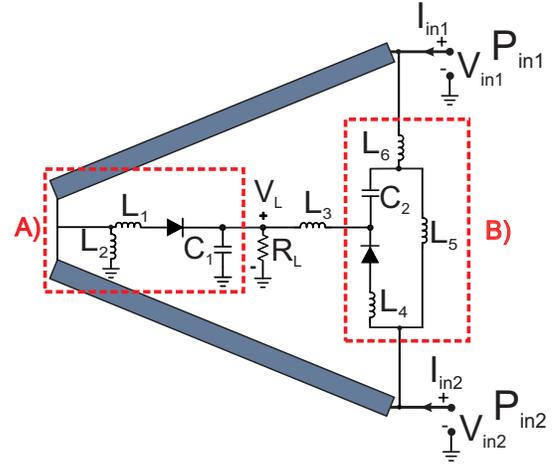


Fig. 2. Circuit of the double design. Two single rectifiers (dash rectangle) have been combined using a common load R_L .

utilizing a nonlinear device to maintain both a high gain and an omnidirectional characteristic for a rectenna.

Some research efforts have been made in harvesting using Wilkinson combiners or dividers. In [14], a rectenna design is proposed and integrated with RFID sensors to harvest ambient power from the RF devices operating in the 2.4 GHz ISM band. The circuit consists of two diode pairs, a Wilkinson power divider, storage and bypass capacitors and an impedance matching circuit. Measured performance for the rectifier is given and shown to be 70% efficient for high power signals of 3 dBm. In [15], the researchers present results of an RF energy harvester at 2.4 GHz WiFi-WLAN frequency band. A Wilkinson's circuit is used to combine the RF signals from two patch antennas and supply a modified Greinacher rectifier. This dc energy is stored in a super capacitor in order to supply on-demand self-powered sensor nodes. The maximum efficiency is measured to be 57.8% at 6 dBm input power. In [16], a method for recycling the wasted power in the isolation resistor of a Wilkinson power combiner is presented when the input signals are not identical. A rectifier is used to replace the isolation resistor of the Wilkinson power combiner to recycle the power that would originally be dissipated in the isolation resistor. It is noticed that only one rectifier circuit is used and the application is to improve the efficiency of power amplifiers (PAs) configured as dual-phase pulse modulated polar transmitters (PMPTs) and therefore it does not convert the RF inputs to dc power.

Our proposed design works in 2.4 GHz ISM band and combines two single diode zero-bias Schottky rectifiers with a conventional Wilkinson circuit in order to be insensitive to the angle of incidence of incoming waves. One rectifier was connected at the output of the combiner. The isolation resistor in the Wilkinson power combiner was replaced by the second a half wave rectifier. To the best of our knowledge, this design is unique because it is used only for RF energy harvesting purposes. The measured RF-to-dc efficiency of the rectifier array was calculated around 16% for in-phase input signals with available input power -17 dBm. When the relative phase of input signals varied from 0 to 360 degrees, a variation in

efficiency between 15.3% and 22% was observed. Preliminary results of this work were presented in [17]. A detailed analysis of the circuit design and optimization is presented here, followed by a number of additional measurements, including efficiency versus load, frequency and phase difference at different power input levels.

The structure of the paper is as follows: Section II provides information about the Wilkinson power combiner circuit. Section III describes the design and implementation of RF-to-dc converter. Section IV presents proof-of-concept experimental results using two continuous signals with different phases. Section V provides the comparison of our work with other similar works at the same frequency band. Finally, section VI includes concluding and future remarks.

II. WILKINSON POWER COMBINER

The conventional Wilkinson power combiner/divider (Fig. 1, a) was invented around 1960 by Ernest Wilkinson [18]. The combiner is ideally lossless when the two input signals are in phase and have identical power ($P_{in,i}$), as the combiner port 3 delivers an output power of $2P_{in,i}$ to the matched output. When only one input signal with power $P_{in,i}$ exists, only $P_{in,i}/2$ of power is delivered to the output and the other half of the power is dissipated in the isolation resistor. Furthermore when the two input signals have a phase difference then a significant amount of energy is dissipated at the resistor.

Our proposed work, uses a Wilkinson combiner connected with two single-diode rectifier circuits for RF energy harvesting. One rectifier is connected at the port 3 as depicted in Fig. 1 (b) in order to deliver the sum of the power. This design exploits the drawback with the non in-phase input signals using a second RF-to-dc rectifier to replace the isolation resistor as shown in Fig. 1 (c). Using this novel topology, the energy that was originally going to be dissipated at the 100 Ω resistor can be captured and supply the load of the system. The second rectifier guarantees wide angular range at the RF inputs. The circuit is called “double” in the following text, it is particularly simple and it can easily be fabricated using lumped components on a printed circuit board (PCB). For benchmarking purposes, a design with one rectifier and an isolation resistor was also fabricated and it is referred as “single”.

III. RF-TO-DC CONVERTER

A. Design

Our initial goal was to increase efficiency and decrease complexity of the circuit. For this reason only one diode was used in each rectifier circuit, since double diode rectification circuits increase losses [19], [20]. For each rectifier, the low-cost Schottky barrier diode SMS7630-040LF from Skyworks Solutions was selected due to its low capacitance of 0.3 pF and the low forward voltage [21]. Since the maximum power transfer occurs when the circuit is matched with the input, impedance matching was performed at a particular available input power of -20 dBm for each input port. The rectifiers were matched to operate simultaneously using a common load

TABLE I
CIRCUIT COMPONENTS FOR THE DOUBLE DESIGN

Name	Value	SMD Package Type	Model
L_1	5.1 nH	0603	0603CS-5N1X_EU
L_2	2.2 nH	0603	0603CS-2N2XJ_EU
L_3	210 nH	0603	0603CS-R21X_EU
L_4	5.6 nH	0603	0603CS-5N6X_EU
$L_{5,6}$	1.8 nH	0603	0603CS-1N8XJEU
$C_{1,2}$	100 pF	0402	-
R_L	1588 Ω	Potentiometer	-
Diode	$L_p = 0.7$ nH, $C_p = 0.25$ pF	SC-79	SMS7630-079LF

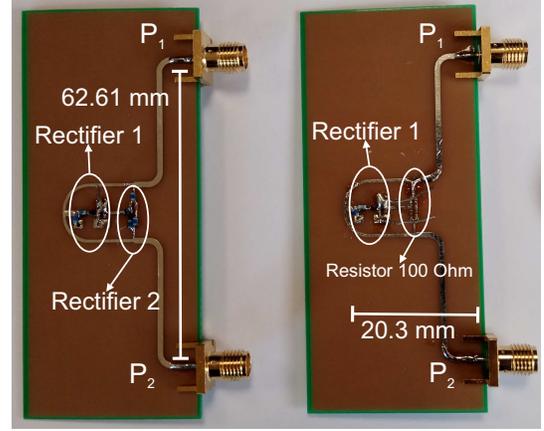


Fig. 3. The two fabricated designs on low cost FR-4 substrate. Left: The “double” design includes two rectifiers. Right: The “single” design includes one rectifier and one isolation resistor.

at the output and the layout of the rectification circuit is shown in Fig. 2. As noted earlier, the RF-to-dc converter consists of two rectifiers with their impedance matching circuits, a Wilkinson power combiner, a storage capacitor (C_1) and a load (R_L) at the output. The matching circuits reduce the reflection losses of the incoming waves, while the capacitor C_1 was introduced in order to stabilize the obtained dc voltage. Finally, the output power supplies the load R_L .

The proposed rectenna was designed and fabricated on a FR-4 substrate in order to decrease the total cost of the design, The FR-4 characteristics were: $\epsilon_r = 4.58$, $\tan \delta = 0.022$, copper thickness 35 μm and substrate height 0.6 mm.

B. Simulation & Optimization

The converter was designed for operation at 2.4 GHz frequency taking into account the Wi-Fi, Bluetooth as well as RFID systems work at ISM 2.4 GHz band. The design were simulated using the Keysight Technologies ADS software with harmonic-balance (HB) analysis. Initially a fixed layout with only the microstrip traces was created and simulated electromagnetically with the method of moments at 2.4 GHz. The goal was to estimate the losses from the low-cost FR-4 substrate and copper and the electromagnetic coupling between the two input ports. Next the layout model was imported into a schematic design and lumped component models were connected with the layout model. HB analysis was applied after that, taking into consideration simultaneously the losses of the substrate, the conductive lines, the components and the non-linear behaviour of the rectifiers due to the diodes.

Multi-objective optimization was used during the simulation process with degrees of freedom only the inductor lumped elements (L) and load R_L . The first optimization goal was the maximization of RF-to-dc efficiency:

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{V_L^2/R_L}{P_{\text{in},1} + P_{\text{in},2}}, \quad (1)$$

with $P_{\text{in},1,2}$ the available power at the two input ports of rectifier, P_{out} the power at load and V_L the voltage across the load R_L . In order to achieve better accuracy in the optimization procedure, a second goal was utilized which was the minimization of reflection coefficient at each input port:

$$\Gamma_{\text{in},i} = \frac{Z_{\text{in},i} - 50}{Z_{\text{in},i} + 50}, \quad (2)$$

assuming input impedance of 50Ω and $Z_{\text{in},i} = V_{\text{in},i}/I_{\text{in},i}$ with $i = 1, 2$. The optimization design parameters were not only the matching network components but also the value of the load at the output. Considering that in a realistic RFID system, the load value is up to $50 k\Omega$ [22], our design could be optimized for a given load value instead of an optimal one. As it is shown in the Section IV, every P_{in} level has an optimum load and thus this approach would be sub-optimum for the efficiency maximization.

After the initial optimization, the ideal lumped elements were progressively replaced by real product S-parameter models provided by the supplier (Coilcraft) and the circuit was re-optimized. The final values and part numbers of the chip inductors and capacitors are given in Table I. The capacitances C_1 , C_2 , and the power $P_{\text{in},i}$ at both inputs ports were fixed at 100 pF and -20 dBm respectively. The obtained optimal lumped element values for the “double” circuit were found as $L_1 = 5.1 \text{ nH}$, $L_2 = 2.2 \text{ nH}$, $L_3 = 210 \text{ nH}$, $L_4 = 5.6 \text{ nH}$, $L_{5,6} = 1.8 \text{ nH}$ and $R_L = 1588 \Omega$. For the “single” design, only the L_1 , L_2 and C_1 components were used with same values as “double” design. In the “single” converter, the second rectifier (Fig. 2, B) was replaced with the 100Ω isolation resistor and the optimum load was found at $R_L = 1759 \Omega$.

C. Fabrication

For validation purposes, the RF-to-dc converters were fabricated as is depicted in Fig. 3. On the right, the PCB of “single” design is depicted. The “double” is shown on the left and contains an extra rectifier instead of the isolation resistor in order to collect the dissipated energy. The design on the right was fabricated for comparison purposes with the design on the left as it can be seen in the next section.

IV. EXPERIMENTAL RESULTS

A. In-Phase Input Measurements

The two converters were measured using a vector network analyser (VNA) at frequencies 1.5 GHz to 3.5 GHz . The input signals were the carrier wave (CW) tones of VNA with $P_{\text{in},1,2} = -20 \text{ dBm}$. The measured S parameters of the “single” and “double” design are shown in Fig. 4 and Fig. 5, respectively. It is shown that the reflection coefficient at each

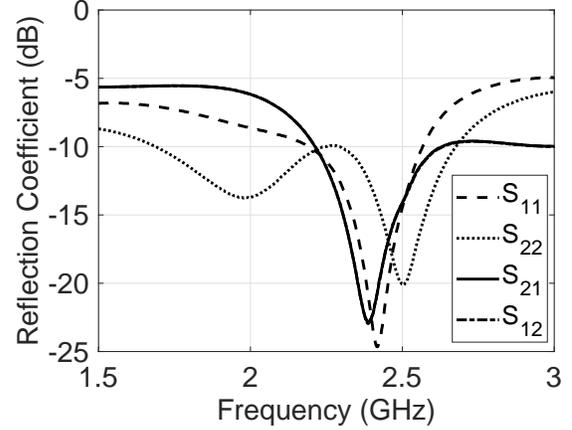


Fig. 4. S-parameters of “single” design. The VNA available input power ($P_{\text{in},i}$) at each port was fixed at -20 dBm .

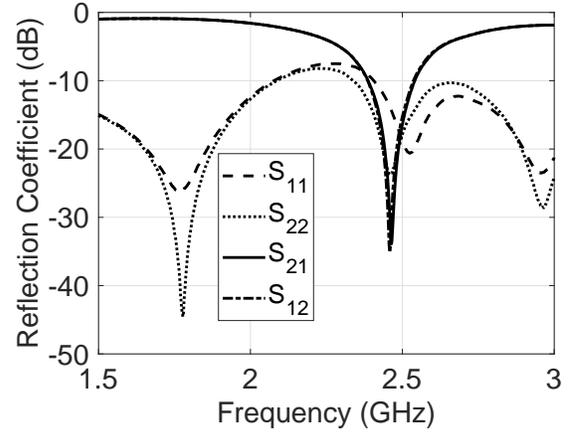


Fig. 5. S-parameters of “double” design. The VNA available input power ($P_{\text{in},i}$) at each port was fixed at -20 dBm .

port (S_{11} and S_{22}) is below -10 dB at the center frequency of 2.4 GHz .

Regarding in-phase input RF signals, a commercial Wilkinson power divider was connected to a signal generator for the efficiency measurements. The divider outputs were connected with board inputs through two “same-length” RF cables. First, a power meter (Keysight U8487A) was connected to each cable, measuring the received power of the signal. Next, the power meter was removed and cables were connected to the proposed “double” design. The total power, P_{in} , is considered as the sum of $P_{\text{in},1}$ and $P_{\text{in},2}$ which are the two divider output ports. A voltmeter measures the voltage across the load, which is fixed at 1588Ω . Fig. 6 depicts the measured results of η versus P_{in} for the “double” design. The efficiency is equal to 29.46% and 9.93% for P_{in} equal to -9 dBm and -21 dBm , respectively. The maximum efficiency was achieved for $P_{\text{in}} = 2 \text{ dBm}$ and it was found at 37% . Fig. 7 shows the measured voltage values across the 1588Ω load. V_L is equal with 51 mV for $P_{\text{in}} = -21 \text{ dB}$ and 240 mV for $P_{\text{in}} = -9 \text{ dBm}$, respectively. Fig. 8 presents the relation between the efficiency and the load only for the “double” design using three power

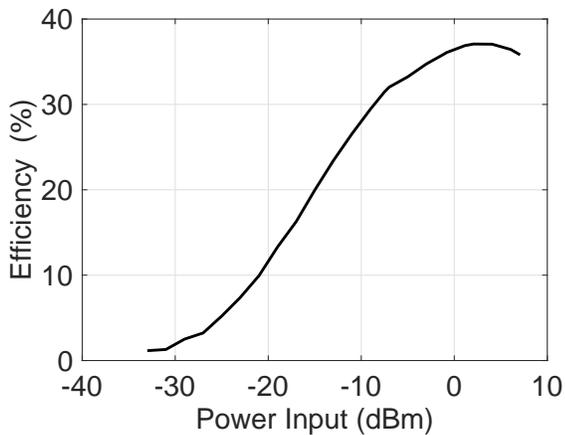


Fig. 6. Measurement rectifier efficiency of “double” design versus the available input power (P_{in}). The two input signals have the same phase at the frequency of 2.4 GHz.

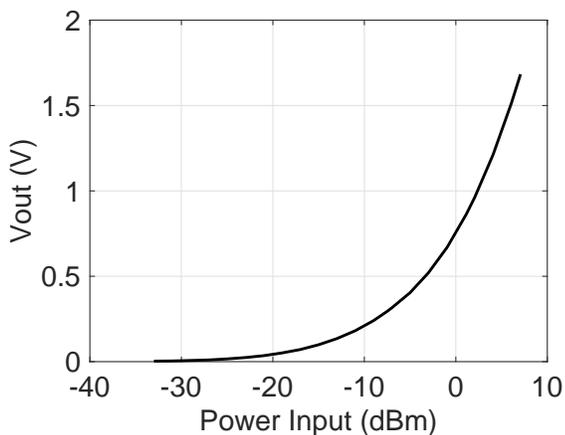


Fig. 7. Measured output voltage of “double” converter across the 1588Ω load. The two input signals have the same phase at the frequency of 2.4 GHz.

input levels, with the frequency fixed at 2.4 GHz. In this case, a commercial potentiometer was used for the load variation instead of a fixed resistor. It is obvious that there is a specific value for the load that maximizes the efficiency for each P_{in} value. More specifically, for $P_{in} = -7$ dBm and $P_{in} = 3$ dBm, maximum efficiency is equal to 27.76% and 39.3% for 1487Ω and 706Ω load, respectively. For $P_{in} = -17$ dBm, the maximum efficiency occurs when $R_L \simeq 1554 \Omega$ as was expected from the simulation results. The measured efficiency versus frequency for different P_{in} and load fixed at 1554Ω , is depicted in Fig. 9. It is shown that “double” converter operates optimally at 2.4 GHz for $P_{in} = -17$ dBm, as expected from the initial design. Also the maximum efficiency is achieved at points very close to 2.4 GHz for the rest of power levels. As can be observed from all above figures, there is a non-linear relation of the efficiency versus the P_{in} , the frequency, as well as load due to the diodes non-linearities.

B. Out-of-Phase Input Measurements

Finally, the two designs were simulated and tested for input signals with different phase each one. Each board was con-

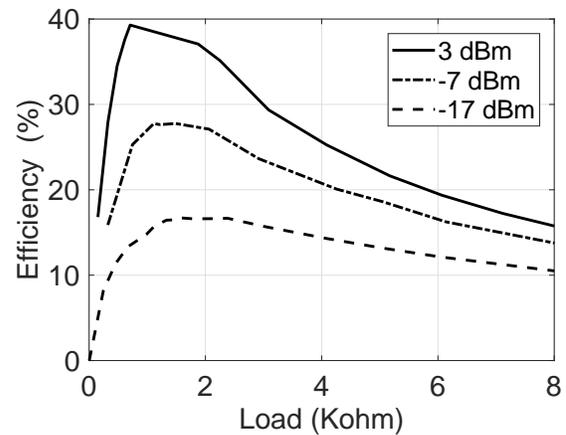


Fig. 8. Measured “double” rectifier efficiency versus load for different available input power at 2.4 GHz.

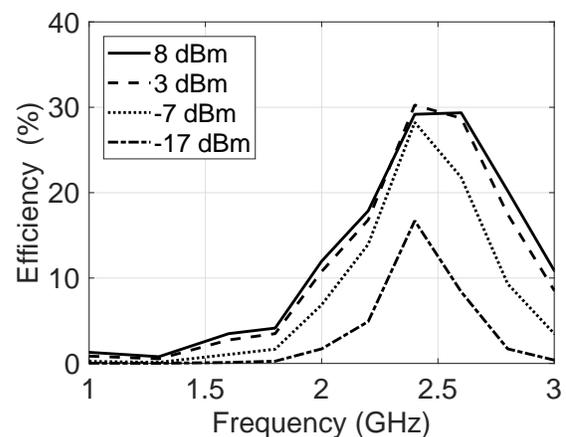


Fig. 9. Measured “double” rectifier efficiency versus frequency for different power input levels. Load is fixed at 1559Ω .

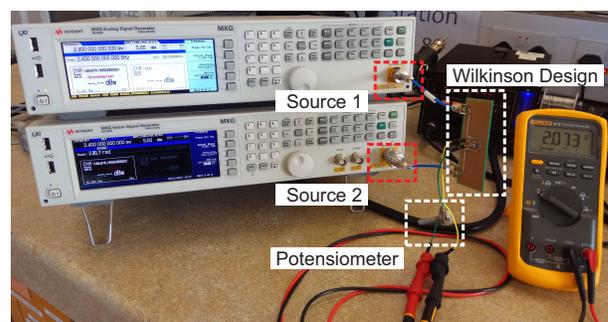


Fig. 10. Two signal generators measurement setup. The one generator has a fixed zero phase 2.4 GHz signal. The second generator was used for the phase sweeping.

nected with two synchronized signal generators simultaneously as depicted in Fig. 10 setup. The generator outputs were connected with boards through the same RF cables that were used in previous results. The first generator was used for phase change from 0 to 360 degrees thus at the second generator, the phase of the signal was fixed at 0 degrees. In Fig. 10 the voltmeter and the potentiometer are also depicted.

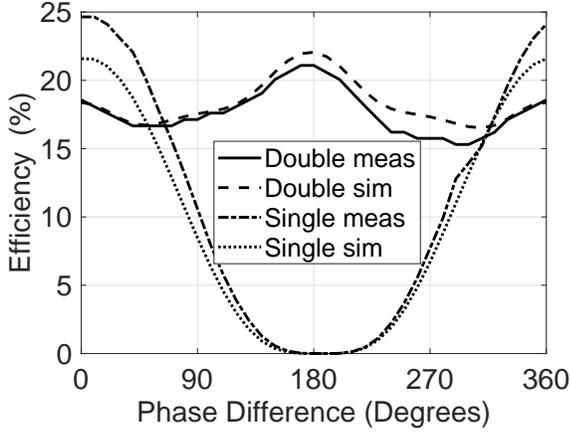


Fig. 11. Simulated and measured converter efficiency versus phase difference at the input. The input signals had frequency 2.4 GHz with $P_{in} = -17$ dBm.

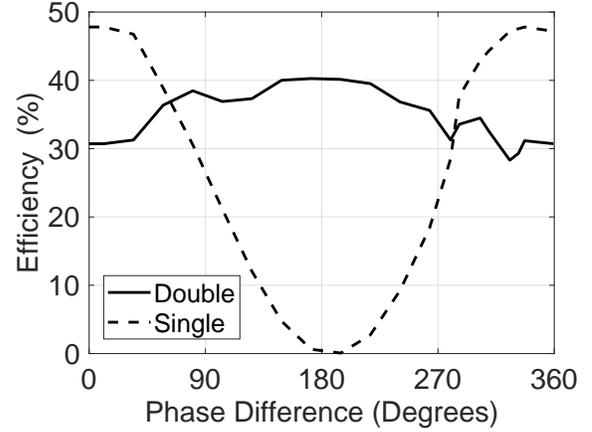


Fig. 13. Measured converter efficiency versus phase difference at the input. The input signals had frequency 2.4 GHz with $P_{in} = 8$ dBm.

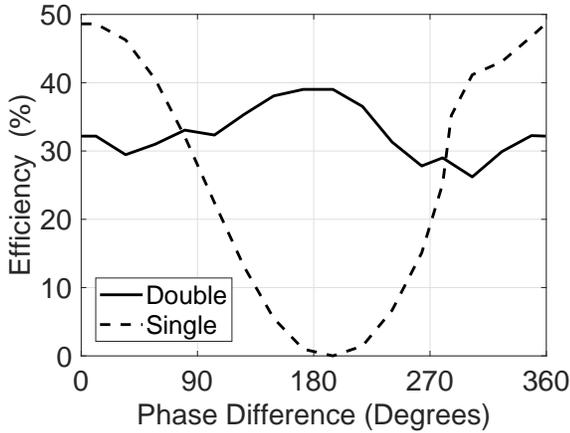


Fig. 12. Measured converter efficiency versus phase difference at the input. The input signals had frequency 2.4 GHz with $P_{in} = 3$ dBm.

Fig. 11 shows the efficiency achieved for $P_{in} = -17$ dBm and phase difference from 0 to 360 degrees. The load for “double” design was fixed at 1554Ω and for “single” at 1759Ω . Very good agreement between simulation and measurements is observed for both designs. For the “single” design, the efficiency is maximized when the input signals are in-phase. Moreover the efficiency goes to zero when the phase difference is 180 degrees and repeats periodically every 360 degrees. The “double” design addresses the problem of the power dissipation on the isolation resistor and when the input signals are out of phase. A constant efficiency is observed between 15.31% and 21.9% from 0 to 360 degrees. In Fig. 12 the measured efficiency versus the phase difference for $P_{in} = 3$ dBm is depicted. The optimal load for the “double” and “single” design was experimentally found at 1022Ω and 909Ω respectively based on the data shown in Fig. 8. The topologies have similar behaviour for a higher P_{in} , as shown in Fig. 11. The maximum efficiency of “double” was measured at 39.02% at 180 degrees and the minimum was 26.2% at 300 degrees. Moreover the “single” had maximum efficiency 48.61% at zero degrees. Finally the efficiency for $P_{in} = 8$ dBm

TABLE II
RF-TO-DC EFFICIENCY FOR FREQUENCY 2.4 GHz.

Work	Type	Ph. Diff. (Deg.)	Eff. (%)	P_{in} (dBm)
[13]	Rectifier	0	43%	-10
[13]	Rectifier	0	10%	-17
[23]	Rectenna	0	50%	-17.2
[24]	Rectenna	0	38.2%	-19.2
[24]	Rectenna	0	15.3%	-9.2
[25]	Rectenna	0	15.7%	-20
[25]	Rectenna	0	42.1%	-10
[26]	Rectenna	0	24%	-17
[26]	Rectenna	0	55%	-7
[27]	Rectenna	0	37%	-25.7
[28]	Rectenna	0	31.8%	-15
This work	Rectifier	0	32%	-7
This work	Rectifier	0	18.5%	-17
This work	Rectifier	180	21.9%	-17
This work	Rectifier	300	15.3%	-17

is shown in Fig. 13. The loads for “single” and “double” designs were fixed at 653Ω and 774Ω , respectively. It can be observed that although the P_{in} has been increased from 3 dBm to 8 dBm, the maximum efficiency cannot go over 40% for the “double” and over 47.8% for the “single” design, due to the breakdown effect of the diodes.

The number of diode elements in the circuit has a major influence on the output voltage of the energy harvesting circuit. Due to the fact that the diodes do not operate as ideal switches, when the number of diodes increases the total power dissipated in the diodes increases. This has an impact in the RF-to-dc conversion efficiency especially at low input power levels. Consequently, a rectifier circuit with one diode presents a higher efficiency than a rectifier circuit with two diodes at low input power level [19]. This is also evident in Fig. 11 when the efficiency of the “single” design is higher than the efficiency of the “double” design.

V. DISCUSSION

Table II offers a summary of achieved efficiency versus input power for various prior art designs operating at the 2.4 GHz

band. We compare rectifiers/rectennas with our design for the in-phase conditions only, however it should be emphasized that our work focused on optimizing efficiency under non in-phase excitation. In order to further increase the efficiency, substrates with low losses [23]–[26] have been proposed. In [23], efficiency was increased to 50% for -17.2 dBm input power level. A circular polarized rectenna was presented in [24] with 15.3% and 11.3% efficiency for vertical and horizontal polarization, respectively. In [25], a dual polarized rectenna consists of a square aperture coupled patch antenna and a rectifier circuit that was optimized at 2.45 GHz with simulated efficiency 15.7% at -20 dBm. In [26] a rectenna is proposed that is formed by a miniaturized 2nd iteration Koch fractal patch antenna and a two-stage Dickson charge pump rectifier. The rectenna achieves a small size with relatively high realized gain (4 dBi) and good conversion efficiency around 24% at -17 dBm. In [27] a fully integrated remotely powered RFID chip is described working at 2.45 GHz. The necessary input power to operate the transponder is about $2.7 \mu\text{W}$. The efficiency of the rectifier circuit is about 37% for -25.7 dBm input power including the antenna effects. In [28], an optimized rectenna structure is presented which eliminates the matching circuit and exhibits the optimal rectifier architecture. The antenna has been configured as an inductively-coupled-feed dipole and it is directly matched to the input impedance of the rectifier. Can be noticed that all the above designs provide efficient results only for in-phase signals.

In [13] a design approach for RF energy harvesting to receive more energy in a wide incident angle range is presented. A beam-forming matrix and a dc power management network are used to the hybrid (RF and dc) power combining. To experimentally verify the proposed hybrid combining array performance, four suspended patch antennas were attached to the RF energy harvesting architecture. More specifically a 4×4 Butler matrix and quadrature hybrids are used for the beam-forming matrix in a hybrid power combining rectenna array. Each port of Butler matrix with 4×4 array antenna has fixed peak gain at a fixed incident wave angle.

Instead of all the designs, the challenge for this work was to design an efficient rectification circuit, working in a wide incident angle range. Our design uses the minimum number of inputs and discrete lumped elements in order to maintain a constant RF-to-dc efficiency over a wide angular range compared to the other designs of table II.

VI. CONCLUSION & FUTURE WORK

In this work, we present a rectifier circuit for RF energy harvesting. Our rectifier combiner do RF power combining and dc power combining in order to achieve a high conversion efficiency with minimum variation from RF signals with arbitrary phase, thereby maintaining both a high gain and an omnidirectional characteristic for a rectenna. A prototype was fabricated on low-cost FR-4 substrate and measurements agreed with simulations.

Nowadays, one of the major research goals is to overcome fundamental challenges related to the miniaturization of electronic circuits in order to scale them up in mmWave

frequencies. The mmWave communications is a key candidate technology for future 5G cellular networks. This is mainly due to the availability of large spectrum resources at higher frequencies, which leads to much higher data rates. Transferring wireless energy, in mmWave frequencies seems attractive for future applications where base stations with directional beamforming capabilities could supply miniaturized low-power devices like RFID tags. The base station/reader could align its narrow beams with the tags in order to supply them with power and the same signals could be also used for the communication links. The proposed system could be miniaturized and applied on passive RFID tag implementations in order to collect energy from multiple directions. Our novel circuit could be also combined with a retro-directive antenna array such a Van Atta array in order to reradiate the signal back to the reader [29]–[31] and at the same time harvest a maximum amount of power independently of the angle of arrival of the incoming reader signal.

ACKNOWLEDGMENT

The authors would like to thank LRF and ICON. The authors would like to thank also all members of Microwaves and Antenna Engineering Research Group, Heriot-Watt University, Edinburgh, Scotland, UK, EH14 4AS for their help in various steps throughout this work.

REFERENCES

- [1] N. Shinohara, "Power without wires," *IEEE Microw. Mag.*, vol. 12, no. 7, pp. S64–S73, Dec. 2011.
- [2] M. Piñuela, P. D. Mitcheson, and S. Lucyszyn, "Ambient RF energy harvesting in urban and semi-urban environments," *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 7, pp. 2715–2726, May 2013.
- [3] K. Niotaki, A. Collado, A. Georgiadis, S. Kim, and M. M. Tentzeris, "Solar/Electromagnetic energy harvesting and wireless power transmission," *Proc. IEEE*, vol. 102, no. 11, pp. 1712–1722, Nov. 2014.
- [4] S. Kim, R. Vyas, J. Bito, K. Niotaki, A. Collado, A. Georgiadis, and M. M. Tentzeris, "Ambient RF energy-harvesting technologies for self-sustainable standalone wireless sensor platforms," *Proc. IEEE*, vol. 102, no. 11, pp. 1649–1666, Nov. 2014.
- [5] W. C. Brown, "The history of power transmission by radio waves," *IEEE Trans. Microw. Theory Techn.*, vol. 32, no. 9, pp. 1230–1242, 1984.
- [6] C. R. Valenta and G. D. Durgin, "Harvesting wireless power: Survey of energy-harvester conversion efficiency in far-field, wireless power transfer systems," *IEEE Microw. Mag.*, vol. 15, no. 4, pp. 108–120, May 2014.
- [7] S. D. Assimonis, S. N. Daskalakis, and A. Bletsas, "Sensitive and efficient RF harvesting supply for batteryless backscatter sensor networks," *IEEE Trans. Microw. Theory Techn.*, vol. 64, no. 4, pp. 1327–1338, Apr. 2016.
- [8] K. Kotani, A. Sasaki, and T. Ito, "High-efficiency differential-drive CMOS rectifier for UHF RFIDs," *IEEE J. of Solid-State Circuits*, vol. 44, no. 11, pp. 3011–3018, Nov. 2009.
- [9] J. Kimionis, A. Georgiadis, and M. M. Tentzeris, "Millimeter-wave backscatter: A quantum leap for gigabit communication, RF sensing, and wearables," in *Proc. IEEE MTT-S Int. Microw. Symp. (IMS)*, Honolulu, HI, USA, Jun. 2017, pp. 812–815.
- [10] T.-H. Lin, S. Daskalakis, A. Georgiadis, and M. M. Tentzeris, "Achieving fully autonomous system-on-package designs: An embedded-on-package 5G energy harvester within 3D printed multilayer flexible packaging structures," in *Proc. IEEE MTT-S Int. Microw. Symp. (IMS)*, Boston, MA, USA, Jun. 2019.
- [11] J. Hester and M. M. Tentzeris, "A mm-wave ultra-long-range energy-autonomous printed RFID-enabled Van-Atta wireless sensor: At the crossroads of 5G and IoT," in *Proc. IEEE MTT-S Int. Microw. Symp. (IMS)*, Honolulu, HI, USA, Jun. 2017.
- [12] B. R. Marshall and G. D. Durgin, "Staggered pattern charge collection: Antenna technique to improve RF energy harvesting," in *Proc. IEEE Int. Conf. on RFID*, Penang, Malaysia, May 2013, pp. 30–35.

- [13] D.-J. Lee, S.-J. Lee, I.-J. Hwang, W.-S. Lee, and J.-W. Yu, "Hybrid power combining rectenna array for wide incident angle coverage in RF energy transfer," *IEEE Trans. Microw. Theory Techn.*, vol. 65, no. 9, pp. 3409–3418, Mar. 2017.
- [14] U. Olgun, C.-C. Chen, and J. L. Volakis, "Low-profile planar rectenna for batteryless RFID sensors," in *Proc. IEEE Antennas and Prop. Society Int. Symp.*, Toronto, ON, Canada, Sep. 2010, pp. 1–4.
- [15] F. Alneyadi, M. Alkaabi, S. Alketbi, S. Hajraf, and R. Ramzan, "2.4 GHz WLAN RF energy harvester for passive indoor sensor nodes," in *Proc. IEEE Int. Conf. on Semiconductor Electronics (ICSE)*, Kuala Lumpur, Malaysia, Oct. 2014, pp. 471–474.
- [16] T. H. Wang and J. H. Chen, "Power recycling using Wilkinson power combiner with pulsewidth modulation," in *Proc. IEEE Int. Symp. on Radio-Freq. Integr. Tech. (RFIT)*, Seoul, South Korea, Sep. 2017.
- [17] S. N. Daskalakis, G. Goussetis, and A. Georgiadis, "A 2.4 GHz rectifier insensitive to the angle of incidence of incoming waves," in *Proc. IEEE 2nd URSI Atlantic Radio Science Meeting (AT-RASC)*, Gran Canaria, Spain, May-Jun. 2018, pp. 1–4.
- [18] E. J. Wilkinson, "An N-way hybrid power divider," *IEEE IRE Trans. Microw. Theory Techn.*, vol. 8, no. 1, pp. 116–118, Jan. 1960.
- [19] P. Nintanavongsa, U. Muncuk, D. R. Lewis, and K. R. Chowdhury, "Design optimization and implementation for RF energy harvesting circuits," *IEEE J. on Emerg. and Select. Topics in Circuits and Systems*, vol. 2, no. 1, pp. 24–33, Mar. 2012.
- [20] A. Boaventura, A. Collado, N. B. Carvalho, and A. Georgiadis, "Optimum behavior: Wireless power transmission system design through behavioral models and efficient synthesis techniques," *IEEE Microw. Mag.*, vol. 14, no. 2, pp. 26–35, 2013.
- [21] *SMS7630 Surface-Mount Mixer and Detector Schottky Diodes, product manual*, Skyworks, Inc., 2018. [Online]. Available: http://www.skyworksinc.com/uploads/documents/Surface_Mount_Schottky_Diodes_200041AD.pdf
- [22] N. Pourmoori, M. W. A. Khan, L. Ukkonen, and T. Björninen, "RF energy harvesting system with RFID-enabled charge storage monitoring," in *Proc. IEEE Conf. on RFID Techn. and Appl. (RFID-TA)*, Macau, China, Sep. 2018, pp. 1–5.
- [23] H. Sun, Y.-x. Guo, M. He, and Z. Zhong, "Design of a high-efficiency 2.45-GHz rectenna for low-input-power energy harvesting," *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 929–932, Aug. 2012.
- [24] A. Georgiadis, G. Andia, and A. Collado, "Rectenna design and optimization using reciprocity theory and harmonic balance analysis for electromagnetic (EM) energy harvesting," *IEEE Antennas Wireless Propag. Lett.*, vol. 9, pp. 444–446, May 2010.
- [25] G. A. Vera, A. Georgiadis, A. Collado, and S. Via, "Design of a 2.45 GHz rectenna for electromagnetic (EM) energy scavenging," in *Proc. IEEE Radio and Wireless Symp. (RWS)*, New Orleans, LA, USA, Mar. 2010, pp. 61–64.
- [26] U. Olgun, C.-C. Chen, and J. L. Volakis, "Wireless power harvesting with planar rectennas for 2.45 GHz RFIDs," in *Proc. IEEE URSI Int. Symp. on Electromagnetic Theory (EMTS)*, Berlin, Germany, Aug. 2010, pp. 329–331.
- [27] J.-P. Curty, N. Joehl, C. Dehollain, and M. J. Declercq, "Remotely powered addressable UHF RFID integrated system," *IEEE J. of Solid-State Circuits*, vol. 40, no. 11, pp. 2193–2202, Oct. 2005.
- [28] Y.-S. Chen and C.-W. Chiu, "Maximum achievable power conversion efficiency obtained through an optimized rectenna structure for RF energy harvesting," *IEEE Trans. on Antennas and Propagation*, vol. 65, no. 5, pp. 2305–2317, Mar. 2017.
- [29] R. Y. Miyamoto and T. Itoh, "Retrodirective arrays for wireless communications," *IEEE Microw. Mag.*, vol. 3, no. 1, pp. 71–79, Aug. 2002.
- [30] J. Cespedes, F. Giuppi, A. Collado, and A. Georgiadis, "A retro-directive UHF RFID tag on paper substrate," in *Proc. IEEE Conf. on RFID Techn. and Appl. (RFID-TA)*, Nice, France, Nov. 2012, pp. 263–266.
- [31] B. D. Braaten, S. Asif, S. Khan, J. Hansen, and D. L. Ewert, "A compact printed Van Atta Array with zero-phase CRLH transmission lines," in *Proc. IEEE Antennas and Prop. Society Int. Symp.*, Vancouver, BC, Canada, Jul. 2015, pp. 1856–1857.



Spyridon Nektarios Daskalakis (S'12) was born in Heraklion, Greece in 1991. He received with excellence his Engineering Diploma and the M.Sc. in Electrical and Computer Engineering from Technical University of Crete (TUC) in 2014 and 2016, respectively. He is currently working toward the PhD degree in School of Engineering and Physical Sciences from Heriot-Watt university, Edinburgh UK.

His current research interests include low-power, low-cost wireless sensor networks and energy harvesting. Particularly he focuses on backscatter radio communication, batteryless sensors, low cost software-defined radio, environmental sensing and RF energy harvesting. He has received fellowship award by the Clinton Global Initiative University 2014 (USA), the Onassis Foundation (graduate studies 2015/16 scholarship), the Lloyds Register Foundation (LRF) and the International Consortium in Nanotechnology (ICON). He was a recipient for two short-term scientific mission grants from COST Action IC1301 WiPE in School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta in 2016, and the Centre Tecnològic de Telecomunicacions de Catalunya, Barcelona in 2015. He is also a recipient of MTT-S Graduate Fellowship for 2019 from IEEE Microwave Theory and Techniques Society. He has been a member of the IEEE Microwave Theory and Techniques Society, the IEEE Council on RFID and the IEEE Sensors Council.



Apostolos Georgiadis (S'94-M'02-SM'08) was born in Thessaloniki, Greece. He received the B.S. degree in physics and M.S. degree in telecommunications from the Aristotle University of Thessaloniki, Thessaloniki, Greece, in 1993 and 1996, respectively, and the Ph.D. degree in electrical engineering from the University of Massachusetts, Amherst, MA, USA, in 2002.

In 2002, he joined Global Communications Devices, North Andover, MA, USA, as a Systems Engineer where he involved in CMOS transceivers for wireless network applications. In 2003, he joined Bermat Inc., Minnetonka, MN, USA, as an RF/Analog Systems Architect. In 2005, he joined the University of Cantabria, Santander, Spain, as a Juan de la Cierva Fellow Researcher. In 2006, he was a consultant for Bitwave Semiconductor, Lowell, MA, USA. He collaborated with ACORDE S.A., Santander, Spain, where he was involved in the design of integrated CMOS VCOs for ultra-wideband applications. In 2007, he joined the Technological Telecommunications Center of Catalonia (CTTC), Spain, as a Senior Researcher of communications subsystems. From 2013 to 2016, he was a Group Leader with the Microwave Systems and Nanotechnology Department, CTTC. In 2016, he joined Heriot-Watt University, Edinburgh, U.K., as an Associate Professor. He has authored more than 180 papers in peer-reviewed journals and international conferences. His current research interests include energy harvesting and wireless power transmission, RFID technology, active antennas and phased-array antennas, inkjet and 3-D printed electronics, millimeter-wave systems.

Dr. Georgiadis was a recipient of the Fulbright Scholarship for graduate studies at the University of Massachusetts, in 1996. He was the General Chair of the 2011 IEEE RFID-TA Conference and the General Co-Chair of the 2011 IEEE MTT-S IMWS on Millimeter Wave Integration Technologies. He is an EU Marie Curie Global Fellow. He is member of the IEEE MTT-S TC-24 RFID Technologies (past Chair) and a member of the IEEE MTT-S TC-26 Wireless Energy Transfer and Conversion. He was an Associate Editor of the IET Microwaves Antennas and Propagation journal, IEEE MICROWAVE AND WIRELESS COMPONENTS LETTERS, and the IEEE RADIO FREQUENCY IDENTIFICATION (RFID) VIRTUAL JOURNAL. He serves as an Associate Editor for the IEEE JOURNAL OF RFID and is the Founder and the Editor-in-Chief of the Wireless Power Transfer Journal of Cambridge University Press. He is the Chair of the URSI Commission D, Electronics, and Photonics, and an AdCom member of the IEEE Council on RFID serving as the Vice President of conferences. He is a Distinguished Lecturer of the IEEE Council on RFID. In 2016, his proposal for Inkjet/3-D printed millimeter-wave systems received the Bell Labs Prize, third place among more than 250 proposals recognizing ideas that "change the game" in the field of information and communications technologies.



George Goussetis (S'99-M'02-SM'12) received the Diploma degree in Electrical and Computer Engineering from the National Technical University of Athens, Greece, in 1998, and the Ph.D. degree from the University of Westminster, London, UK, in 2002. In 2002 he also graduated B.Sc. in physics (first class) from University College London (UCL), UK.

In 1998, he joined the Space Engineering, Rome, Italy, as RF Engineer and in 1999 the Wireless Communications Research Group, University of Westminster, UK, as a Research Assistant. Between 2002

and 2006 he was a Senior Research Fellow at Loughborough University, UK. He was a Lecturer (Assistant Professor) with Heriot-Watt University, Edinburgh, UK between 2006 and 2009 and a Reader (Associate Professor) with Queen's University Belfast, UK, between 2009 and 2013. In 2013 he joined Heriot-Watt as a Reader and was promoted to Professor in 2014, where he currently directs the Institute of Sensors Signals and Systems. He has authored or co-authored over 500 peer-reviewed papers five book chapters one book and four patents. His research interests are in the area of microwave and antenna components and subsystems.

Dr. Goussetis has held a research fellowship from the Onassis foundation in 2001, a research fellowship from the UK Royal Academy of Engineering between 2006-2011 and European Marie-Curie experienced researcher fellowships in 2011-12 and again in 2014-17. He is the co-recipient of the 2011 European Space Agency young engineer of the year prize, the 2011 EuCAP best student paper prize, the 2012 EuCAP best antenna theory paper prize and the 2016 Bell Labs prize. He has served as Associate Editor to the IEEE Antennas and Wireless Propagation Letters.



Manos M. Tentzeris (S'89-M'98-SM'03-F'10) received the Diploma Degree in Electrical and Computer Engineering from the National Technical University of Athens ("Magna Cum Laude") in Greece and the M.S. and Ph.D. degrees in Electrical Engineering and Computer Science from the University of Michigan, Ann Arbor, MI and he is currently Ken Byers Professor in Flexible Electronics with School of ECE, Georgia Tech, Atlanta, GA

He has published more than 650 papers in refereed Journals and Conference Proceedings, 5 books and

25 book chapters. Dr. Tentzeris has helped develop academic programs in 3D/inkjet-printed RF electronics and modules, flexible electronics, origami and morphing electromagnetics, Highly Integrated/Multilayer Packaging for RF and Wireless Applications using ceramic and organic flexible materials, paper-based RFID's and sensors, wireless sensors and biosensors, wearable electronics, "Green" electronics, energy harvesting and wireless power transfer, nanotechnology applications in RF, Microwave MEM's, SOP-integrated (UWB, multiband, mmW, conformal) antennas and heads the ATHENA research group (20 researchers). He has served as the Head of the GT-ECE Electromagnetics Technical Interest Group, as the Georgia Electronic Design Center Associate Director for RFID/Sensors research and as the Georgia Tech NSF-Packaging Research Center Associate Director for RF Research and the RF Alliance Leader. He was the recipient/co-recipient of the 2017 Georgia Tech Outstanding Achievement in Research Program Development Award, 2016 Bell Labs Award Competition 3rd Prize, the 2015 IET Microwaves, Antennas and Propagation Premium Award, the 2014 Georgia Tech ECE Distinguished Faculty Achievement Award, the 2014 IEEE RFID-TA Best Student Paper Award, the 2013 IET Microwaves, Antennas and Propagation Premium Award, the 2012 FiDiPro Award in Finland, the iCMG Architecture Award of Excellence, the 2010 IEEE Antennas and Propagation Society Piergiorgio L. E. Uslenghi Letters Prize Paper Award, the 2011 International Workshop on Structural Health Monitoring Best Student Paper Award, the 2010 Georgia Tech Senior Faculty Outstanding Undergraduate Research Mentor Award, the 2009 IEEE Transactions on Components and Packaging Technologies Best Paper Award, the 2009 E.T.S. Walton Award from the Irish Science Foundation, the 2007 IEEE APS Symposium Best Student Paper Award, the 2007 IEEE IMS Third Best Student Paper Award, the 2007 ISAP 2007 Poster Presentation Award, the 2006 IEEE MTT Outstanding Young Engineer Award, the 2006 Asian-Pacific Microwave Conference Award, the 2004 IEEE Transactions on Advanced Packaging Commendable Paper Award, the 2003 NASA Godfrey "Art" Anzic Collaborative Distinguished Publication Award, the 2003 IBC International Educator of the Year Award, the 2003 IEEE CPMT Outstanding Young Engineer Award, the 2002 International Conference on Microwave and Millimeter-Wave Technology Best Paper Award (Beijing, CHINA), the 2002 Georgia Tech-ECE Outstanding Junior Faculty Award, the 2001 ACES Conference Best Paper Award and the 2000 NSF CAREER Award and the 1997 Best Paper Award of the International Hybrid Microelectronics and Packaging Society. He was the TPC Chair for IEEE IMS 2008 Symposium and the Chair of the 2005 IEEE CEM-TD Workshop and he is the Vice-Chair of the RF Technical Committee (TC16) of the IEEE CPMT Society. He is the founder and chair of the RFID Technical Committee (TC24) of the IEEE MTT Society and the Secretary/Treasurer of the IEEE C-RFID.

He is the Associate Editor of IEEE Transactions on Microwave Theory and Techniques, IEEE Transactions on Advanced Packaging and International Journal on Antennas and Propagation. Dr. Tentzeris was a Visiting Professor with the Technical University of Munich, Germany for the summer of 2002, a Visiting Professor with GTRI-Ireland in Athlone, Ireland for the summer of 2009 and a Visiting Professor with LAAS-CNRS in Toulouse, France for the summer of 2010. He has given more than 100 invited talks to various universities and companies all over the world. He is a Fellow of IEEE, a member of URSI-Commission D, a member of MTT-15 committee, an Associate Member of EuMA, a Fellow of the Electromagnetic Academy and a member of the Technical Chamber of Greece. Prof. Tentzeris served as one of the IEEE MTT-S Distinguished Microwave Lecturers from 2010-2012 and he is one of the IEEE CRFID Distinguished Lecturers.